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Observations on Natural Regeneration in Ponderosa Pine Following a Prescribed Fire in Arizona

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A good seed crop, coupled with a prescribed burn, designed to reduce fuels in an undisturbed stand of ponderosa pine (*Pinus ponderosa* Laws.), resulted in the establishment of many pine seedlings. In addition to an adequate seed source which was being dispersed during the fall burning, conditions that appeared to favor germination and survival included a more receptive seedbed, increased nutrient availability, and more favorable conditions of soil moisture and temperature.

Keywords: *Pinus ponderosa*, prescribed burning, natural regeneration, seedbed preparation

MANAGEMENT IMPLICATIONS

Except in isolated situations, attempts to regenerate southwestern ponderosa pine stands naturally or by direct seeding have been a failure (Heidmann et al. 1977). Planting is expensive and not always successful. Using prescribed fire to prepare a site for regeneration may be cost effective in openings that are too small for planting. Interval prescribed burning can provide continuous hazard abatement and, at the same time, maintain a favorable seedbed for natural regeneration. Deferring burning for a few years after germination may be needed to permit seedlings to become large enough to resist damage when the burning rotation is resumed.

INTRODUCTION

Natural ponderosa pine regeneration has not been abundant in the Southwest for the past 50 years (Schubert et al. 1970). Schubert (1974) identified several conditions needed to successfully regenerate southwestern ponderosa pine, both naturally and artificially. Ini-

tially, an adequate seed source and/or healthy, adaptable planting stock is needed. Assuming this resource is available, the important criteria include a well-prepared site where competition is controlled, and there is adequate moisture (amount and timing), appropriate shade, and protection from birds and rodents, insects, and browsing animals.

Marked reductions in germination stem from high moisture stress (Larson and Schubert 1969). Lowdermilk (1930) suggested that the best seedbed is made up of a loose soil with adequate needle litter to cover the seeds, and facilitate precipitation penetration and moisture conservation. Rowe (1955) pointed out that one-half inch of forest floor is optimum for moisture retention. Krauch (1936) and Pearson (1950) emphasized that pine litter is needed to prevent excessive soil drying and to protect the seed from birds and rodents.

Accumulation of litter fuels also contributes to the difficulty of getting natural regeneration established. Most ponderosa pine stands in the Southwest have accumulated large amounts of surface fuels since fire suppression began shortly after 1900. Fuel loadings of 8.3 to 20.4 tons per acre (13.5 tons per acre average) are common for unburned, relatively undisturbed ponderosa pine stands in Arizona (Sackett 1979). Fuel depth around large, mature trees (yellow pine sites), where new seedlings would be most appropriate to perpetuate the stand, can average more than 3.5 inches with a corresponding average weight of roughly 39 tons per acre.

¹Research Forester. Headquarters is in Fort Collins, in cooperation with Colorado State University. Research reported here was conducted at the Station's Research Work Unit at Tempe, in cooperation with Arizona State University.

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This heavy mat of dead material can reduce the chance for seeds to reach mineral soil, where germination can take place most effectively. Forest floor material in the F-layer in undisturbed stands is tightly held together by mycelial hyphae. Haase (1981) found that the bond is even tighter at the F- and H-layer interface, and that 85% of the seeds never penetrate the H-layer to reach mineral soil under these mature ponderosa pines.

Heavy litter layers also inhibit moisture penetration. Although seeds will germinate in duff moistened by summer rains, the seedlings usually die when their roots fail to reach mineral soil before the onset of fall drought conditions.

Adequate site preparation is a major problem. Heavy equipment is expensive, and because ponderosa pine typically grows in even-aged groups within uneven-aged stands, the use of such equipment is ineffective as a site preparation measure, except in very open or heavily logged stands. Equipment use is restricted by rocky terrain. Stands opened by logging and/or invaded by grass and other herbaceous vegetation often require expensive treatment with herbicide to prepare the site (Heidmann 1969). Planting may be the only alternative when entire areas are completely denuded by late spring-early summer wildfires. The high cost of seed and site preparation makes direct seeding almost as costly as planting (Heidmann et al. 1977). Planting costs for the Forest Service in Arizona and New Mexico varied from \$278 to \$1,423 per acre in 1981, depending on the site; the average was \$278 per acre.² First-year survival of bare root stock seedlings in this same region ranged from 39% to 80% in 1981. The weighted average based on acres sampled was 53%. Despite the high costs, poor survival, and technical difficulties, thousands of acres are planted each year, and sometimes replanted, in an effort to achieve adequate stocking.

Little reliance is placed on natural regeneration as a valid method for perpetuating ponderosa pine in the Southwest, despite the fact that natural regeneration, responding to an environment in which fire has played an important role, has been sufficient to insure perpetuation of the species (Cooper 1960, 1961; Weaver 1951). Climate, competing vegetation, moisture deficiency, and impact of insects and mammals have all been blamed for inadequate regeneration. Yet, there is seldom a reference made in silviculture literature to the virtual elimination of fire—a natural element in the ecosystem—as a possible cause of the failure.

Historically, fire has been a dominant feature in the ecology of ponderosa pine in the Southwest (Dieterich 1980a, 1980b), influencing these stands at intervals that are more frequent (1.8-2.4 years) than intervals for expected good seed years—4.8 years (Schubert 1974). Heidmann et al. (1982) described a procedure for establishing natural regeneration on the Apache-Sitgreaves National Forest in which mechanical discing was used, supplemented with rodent control and protection from grazing. These are expensive treatments and are difficult to coordinate with years having adequate

seed crops. Biswell (1963) and Weaver (1968) encouraged the use of prescribed fire to manage the species, and recognized the importance of the role of fire in encouraging natural regeneration. This note reports on some observations of natural regeneration after an initial prescribed fire at the Chimney Spring Interval Burning Study Area near Flagstaff, Ariz.

STUDY AREA

In 1976, a long-term study designed to determine optimum burning intervals needed to provide continuous fire hazard abatement was established on the Fort Valley Experimental Forest, near Flagstaff, Ariz. Soil on the Chimney Spring study area is volcanic in origin and is tentatively classified as Brolliar stoney clay loam.³ Elevation averages 7,450 feet; annual precipitation is about 22 inches per year (Schubert 1974).

Timber on the site is essentially undisturbed and is typical of the stand structure in southwestern ponderosa pine—uneven-aged stands made up of small even-aged groups. The original stand averaged 1,875 stems per acre; basal area was 144 square feet per acre. Site index was 75, based on 100 years. Yellow pine sites occupied 17.3% of the area; pole stands 62%; dense sapling/small pole stands (doghair thickets) 17%; and openings with no overstory 3.7%. An average of 39 trees per acre occupied the yellow pine sites.

Forest floor material less than 1-inch diameter averaged more than 15 tons per acre, of which 6.2 tons per acre was humus. Woody material greater than 1-inch diameter added an additional 7.2 tons per acre to the forest floor. A fire history study for the Chimney Spring area indicated that the site had not been burned in the previous 100 years (Dieterich 1980a).

METHODS

On November 5, 1976, after a dry summer and fall, the area was treated with an initial fuel reduction prescribed burn (Sackett 1980). Eighteen 2.5-acre plots were burned. Three plots were left unburned as controls. Forest floor material less than 1-inch diameter was reduced 63% and larger material 69%. Mineral soil was exposed on about 19% of the area, mostly around large, mature trees and where rotten logs were consumed (Sackett 1980).

Although there were no plans to investigate natural regeneration during the first stages of the study, 8 one-quarter mil-acre quadrats were systematically established in July 1977 on each plot to monitor germination and survival as seedlings started to appear. Additional information on seedling germination and survival was obtained from permanent transects installed to inventory understory vegetation.

³Meurisse, Robert T. 1971. *Soils report, San Francisco Peaks area, Elden and Flagstaff Ranger Districts, Coconino National Forest. USDA Forest Service, Mimeo Report, 47 p. Division of Watershed Management, State and Private Forestry, Southwestern Region, Albuquerque, New Mex.*

²Personal communication from Steve Romero, USDA Forest Service, Southwestern Region, Albuquerque, N. Mex.

When the one-quarter mil-acre plots and vegetative transects were inventoried 1 year later, an insufficient number of seedlings were present to effectively monitor overall regeneration progress. Because enough seedlings were available on other portions of the 2.5-acre study plots, an additional 25 seedlings were selected and tagged for study on each of the 18 burned plots. A total of only eight seedlings were found and tagged for study on the control plots.

Seedling surveys made in spring 1980 indicated a discrepancy between number of seedlings identified in the original sample and what was actually happening on the plots. Very few sample seedlings remained; yet, there were still many 1977 seedlings present on the burned plots. Prior to burning in fall 1980, all seedlings were located, measured, and tagged on the 1-, 2-, and 4-year rotation plots. In spring 1981, all seedlings on the 6-, 8-, and 10-year plots were also tallied.

RESULTS AND DISCUSSION

Seedlings began to appear soon after the summer rains started in mid-July 1977, and were concentrated in areas where forest floor consumption was sufficient to expose some mineral soil—generally on yellow pine sites and where heavy fuels were consumed. Needle-cast from November to time of germination provided a fresh litter layer of 300-475 pounds per acre⁴ that protected the seeds from predators and conserved soil moisture. Partial shading was provided by the overstory, charcoal chunks, and unconsumed branches and logs. The greatest concentrations of seedlings appeared to be on the northeast side of seed trees.

The first seedling inventory was made in August 1977 as the seedlings began to germinate. Inventories on burned plots indicated an equivalent of more than 2,600 seedlings per acre. Thirty-eight percent of the quadrats had at least one seedling. Inventories on unburned controls showed 833 seedlings per acre; 17% of the quadrats had at least 1 seedling. Table 1 summarizes the initial seedling count of burned treatment and control plots.

A vegetation survey in the fall of 1977 resulted in additional seedling germination data. Understory vegetation, including seedlings, was sampled on four permanent transects in each plot. Table 2 shows the percent stocking on burned plots and unburned controls. The burning treatments had 63% better stocking than the unburned controls. Stocking percentages are not the same for the two sampling schemes because of differences in quadrat size, placement, and sampling intensity. However, both methods confirm that burned treatments produced better germination success.

Seedbed conditions were examined where each seed germinated on the one-quarter mil-acre quadrats (table 3). Seven of the 101 seedlings became established on forest floor having L-, F-, and H-layers intact. Five of those were on unburned controls. One seedling was

established where only the L-layer was present. In all other cases (93), seeds germinated where fire had consumed all or part of the forest floor. Fifty-eight percent of the seedlings became established on mineral soil or where thin layers or chunks of carbonized material were present on the soil surface. The remainder of the seeds (39%) germinated where fire had eliminated the L-layer or the L- and F-layers of forest floor material. The burned seedbeds had a thin protective layer of new

Table 1.—Ponderosa pine germination at Chimney Spring, August 1977

Treatment	Germinated seeds ¹	Quadrats stocked ²	Percent stocking
Unburned plots (3)	5	4	17
Burned plots (18)	96	54	38

¹Seedlings germinating in 8 one-quarter mil-acre quadrats per plot.

²One-quarter mil-acre quadrats with at least one seedling.

Table 2.—Ponderosa pine seedling stocking on vegetation survey quadrats, Chimney Spring, 1977

Treatment	Quadrats stocked ¹	Percent stocking
Unburned plots (3)	21	3.5
Burned plots (18)	206	5.7

¹Number of 20- × 50-cm quadrats with at least one seedling in it, 200 per plot.

Table 3.—Type of seedbed where germination took place at Chimney Spring, 1977

Treatment	Seedbed classification ¹									Total
	LFH	L	F	FH	H	M	A	CF	CH	
----- number of seedlings -----										
Unburned plots (3)	5									5
Burned plots (18)	2	1	25	8	5	25	3	13	14	96

¹LFH = All three forest floor layers intact, no fire over area.

L = newly cast needles on naturally bare soil, no fire over area.

F = F layer intact but charred on top surface from L layer being burned, no H layer below. FH = F and H layers intact but charred on top surface from L layer being burned. H = H layer intact but charred on top surface from L and F layers being burned. M = Mineral soil, all material consumed on site. A = Mineral soil, but chunks of charcoal from partially eliminated woody material. CF = F layer charred heavily, L layer burned off and no H layer below. CH = H layer charred heavily, L and F layers burned off.

⁴Data on file with the Fire Effects Project, Rocky Mountain Forest and Range Experiment Station, Tempe, Ariz.

needles that had been cast after the fire and before germination. Results indicate that germination success was better on areas experiencing the heaviest fire disturbances. To further illustrate the benefit of exposed mineral soil in pine regeneration, the correlation between quadrat bare area (square feet) for each burning treatment and quadrats stocked is $r = 0.92$.

Haase (1981), in a companion study at Chimney Spring, found that seeds falling on undisturbed forest floor seldom reached mineral soil. Only three seedlings (1% of total) were located on unburned sites, and all were in mineral soil with a light accumulation of new needles—usually beyond tree canopies.

Seedling Establishment

To become established and survive, seedlings must develop a long tap root to avoid desiccation from fall drought and resist frost heaving. Schubert (1974) and Pearson (1950) contended that precipitation in the Southwest is rarely sufficient for good germination. This contention was not substantiated by this study. Moisture conditions during the winter (1976-1977), and spring and summer (1977) were marginal for seedling germination and survival. Rainfall at Fort Valley Experimental Forest Headquarters site, 3 miles from the Chimney Spring plots, was 7.19 inches below normal for this period. Despite this deficit, seed germination and early survival on the Chimney Spring plots was excellent.

By October 1977, four of the five seedlings on the unburned control plots died. The burned plots lost 5 of their original 96 tagged seedlings. Favorable initial seedling development on burned plots was attributed to: (1) availability of a good seedbed, (2) improved moisture relations, (3) more favorable soil temperatures (warmer), and (4) availability of nutrients released by the fire. Ryan (1978), working on the same study area, discovered that soil moisture on burned yellow pine sites was higher in late July and through August 1977 (18.9%) than similar areas on unburned controls (15.2%). Haase (1981) found the same moisture relationship in a regeneration study at Chimney Spring. Soil temperatures on burned and unburned sites adjacent to Chimney Spring revealed that burned areas averaged 9° F warmer for the time period for active germination (Milne 1978). Although soil moisture, soil temperature, and mineral soil seedbeds are important to good germination and establishment, increased availability of nutrients released by the fire may be the most crucial stimulus. Larson (1961) suggested that, on basalt soils, no amount of water or protection will produce seedlings strong enough to survive the combination of fall drought, first winter frost heaving, and spring drought common to the Southwest. This would suggest that some other variables were at work to produce so many healthy seedlings. Nutrient release from prescribed fire in Southwest ponderosa pine forests has been documented (Ryan 1978). Analysis of data taken at Chimney Spring in 1977 shows much greater concentrations of ammonium and nitrate soil nitrogen on burned plots—especially heavily burned yellow pine sites.

First-Year Survival

By June 1978, burned plot seedlings on one-quarter mil-acre quadrats were reduced an additional 47% by winter losses. Losses came from late fall and early spring drought or from frost heaving. Because first year seedlings are so small, it is difficult to assess actual cause of death. Heidmann (1976) stated that frost heaving may be the leading cause of mortality in first-year ponderosa pine seedlings, in northern Arizona. Seedlings that made it through the first winter were vigorous and well developed. Large "crowns" and heavy stems allow seedlings to sway in the wind, creating an open ring around them in the soil (Schramm 1958). This open collar prevents the soil from freezing and gripping the stem and, hence, pulling it out of the ground as the ice-laden soil heaves.

Second-Year Survival

The 1- and 2-year rotation plots lost five more seedlings on the one-quarter mil-acres, between spring and fall of 1978. Burning in the fall further reduced their numbers, leaving those rotations with only 5 of their original 32 seedlings. After the second winter, burned plot seedlings were reduced to 19 seedlings—20% of original samples. The control plots no longer had any seedlings remaining. Figure 1 summarizes the losses from the time of germination through spring 1979 and beyond.

Additional Seedlings Monitored

As mentioned earlier, 25 seedlings on each burn treatment plot and the 8 seedlings found on the control plots were tagged to monitor survival and identify causes of mortality. Although late spring and early summer rainfall was below normal (-2.79 inches), the newly selected seedlings progressed well during the first full growing season. Prior to the fall burning treatment, seedlings on the 1- and 2-year burning rotations suffered a 2.7% loss. Seventeen percent of the remainder were lost to the fires. The fuel mosaics that occur in ponderosa pine stands and "moist" burning conditions produced spotty burning and low intensity fires that allowed a considerable number of seedlings to survive. These fall fires eliminated only a few more seedlings than were lost from natural causes. As litter fuels accumulate, fire intensities increase and burned area coverage is more complete. Direct fire losses accounted for 31% of seedling mortality on plots having fire treatments after germination.

The period between snowmelt and the summer monsoons is critical to seedling survival. Winterkill is often caused by severe drying (Bates 1923, Pearson 1931), and spring drought can cause additional seedling loss. After the summer monsoons subside, seedlings again may be exposed to the common early fall dry period, and many do not survive. Drought caused a heavy toll on seedlings at Chimney Spring, but, because of sampling schedules,

it was difficult to determine which drought period caused the death. All drought mortality was combined in table 4. Drought was the leading cause of mortality (52%) among seedlings.

Frost heaving may remain a problem for first-winter seedlings. If a seedling remains stunted or for some reason cannot form a void in the soil around its stem, the chances of it being frost-heaved appear high. Frost heaving accounted for about 16% of the deaths.

Browsing animals are a threat to seedling survival. Although confirmed deaths caused by browsing were only 3%, many seedlings continued to be clipped regularly. Many of these seedlings are currently stunted or deformed and have one or more lateral branch leaders. Unknown and other causes such as root rots, foliage fungus, and smothering from fallen debris make up the remaining causes of death (15%).

Unburned control plot seedlings fared well during the first full growing season, but by the next fall (1979), all had succumbed. Figure 2 and table 4 show survival progression and causes of seedling deaths. Figure 3 shows the vigor of a burned area seedling—presumably a result of enhanced environmental conditions.

By fall 1981, only 12% of the original 458 tagged seedlings remained (25 on each burned plot, 8 on control plots). After four full growing seasons, seedling survival on burned plots was 6%. Plots that were initially burned but not subsequently exposed to fire had 19% remaining.

All Seedlings Counted and Monitored

Prior to the 1980 fire treatment, all seedlings (from 1976 seedfall) were counted and tagged for continued monitoring on 1-, 2-, and 4-year rotations (table 5). After three fires, the plots burned annually still contained 143 seedlings. The 2-year rotation plots with one interim fire had 386, and the 4-year rotations had 725. Weather and fuel moisture conditions were severe in October 1980 and produced fireline intensities in 4-year fuel accumulations that were comparable to some wildfires (260-650

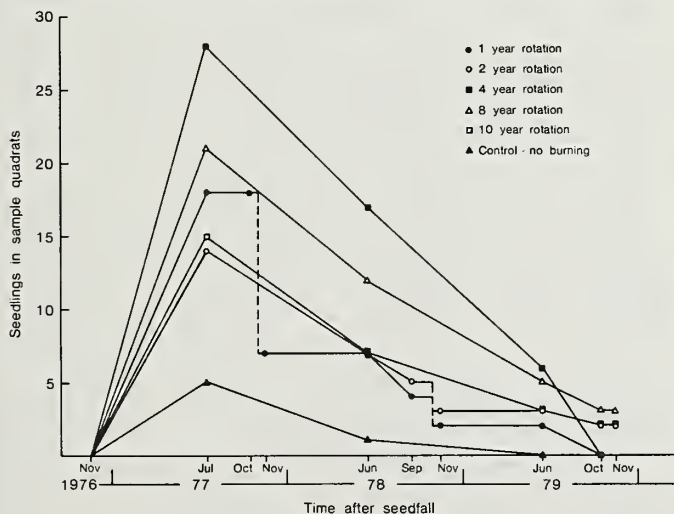


Figure 1.—Survival of originally established seedlings at Chimney Spring, 1977.

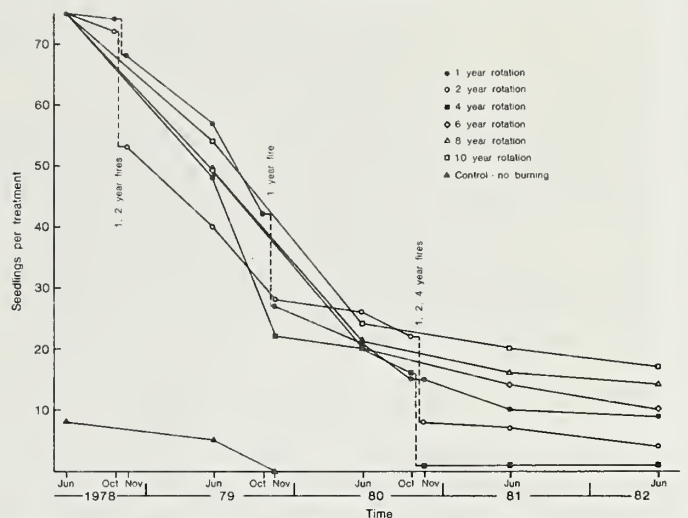


Figure 2.—Survival of seedlings selected 1 year after germination at Chimney Spring.

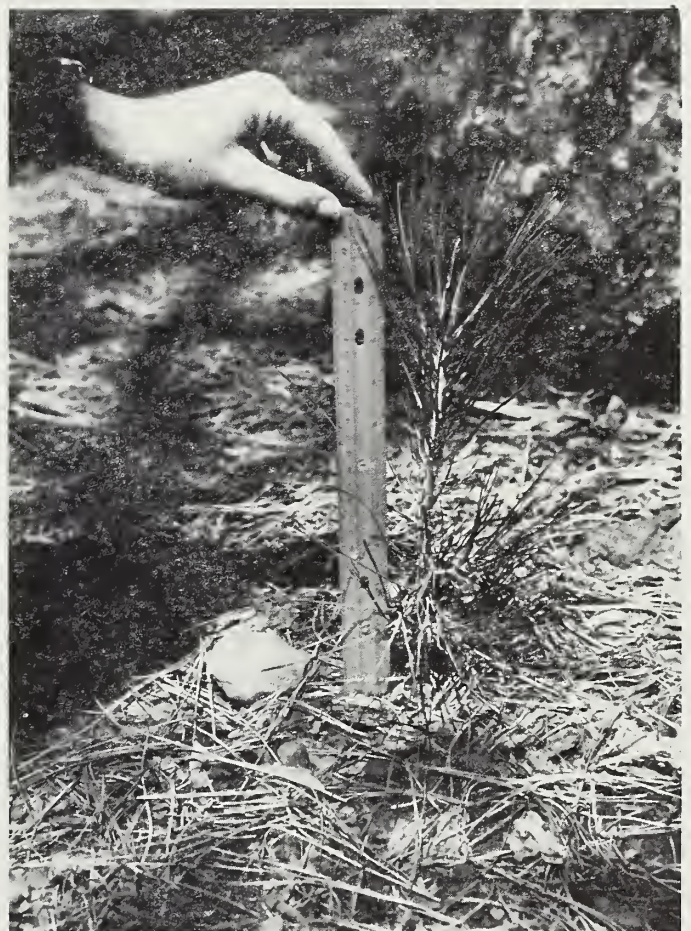


Figure 3.—Vigorous 9-inch seedling 2 years after germination—probably a result of nutrients released by 1976 fire.

Btu's/sec/fireline ft). Both annual and biennial fires in 1980 burned more intensely than in previous years. Ninety-four percent of the seedlings that survived four growing seasons (4-year rotation) were destroyed in these early fall fires. The annual plots burned unevenly and with lower fire intensities, allowing a greater pro-

Table 4.—Probable cause of death (by percentage) to seedlings selected one year after germination at Chimney Spring, 1978–1982

Treatment	Cause of death				
	Drought/ winterkill	Frost heaving	Fire	Browsed by animal	Unknown and other
Unburned controls	37	13	NA	0	50
1-year burning rotation ¹	70	9	17	0	4
2-year burning rotation ²	25	10	56	3	6
4-year burning rotation ³	50	20	20	2	8
6-year burning rotation ⁴	52	13	NA	3	32
8-year burning rotation ⁴	48	28	NA	6	18
10-year burning rotation ⁴	67	9	NA	2	22

¹Three fires after seedling selection.

²Two fires after seedling selection.

³One fire after seedling selection.

⁴No fires after seedling selection.

Table 5.—Ponderosa pine seedlings remaining at Chimney Spring from 1977 germination¹

Treatment	Fall 1980 Number		Spring 1981 Number	Spring 1982			Stocking
				Number	Aver. height	Range	
					----- inches -----		trees/acre ⁵
Unburned controls	—		0	0	—	—	—
1-year burning rotation	² 143	FIRE	72	43	5.0	(1.6– 9.3)	94
2-year burning rotation	³ 386	FIRE	49	43	5.9	(2.1–15.3)	24
4-year burning rotation	⁴ 725	FIRE	43	40	8.7	(3.9–29.8)	30
6-year burning rotation	—		³ 195	222	5.6	(1.9–17.1)	110
8-year burning rotation	—		³ 246	283	4.6	(1.7–27.1)	120
10-year burning rotation	—		³ 183	165	5.1	(1.5–14.4)	130

¹One-hundred percent survey of all seedlings.

²After three fires.

³After one fire.

⁴No fire after germination.

⁵Acres considered are only those that need restocking, i.e., yellow pine sites, around snags, and openings.

portion of seedlings to survive (50%) than on the 2-year rotation (13%) and the 4-year rotation (6%). Most of the seedlings that survived the 1980 fires were located on sites where fuel was sparse or discontinuous.

In spring 1981, all surviving seedlings that germinated in 1977 were located, tagged, and measured on every plot. Table 5 illustrates the results of that survey. These surviving seedlings were found primarily in openings, around snags, and on burned-over yellow pine sites. After 5 growing seasons, combined burning treatments averaged 86 seedlings per "acceptable" acre. That is the area in openings where regeneration is most needed. Burned treatments that have not had fires since seed germination averaged 119 seedlings per "acceptable" acre. Burned treatment plots that had not been returned since 1976 averaged 119 seedlings per acre in the openings where regeneration is needed. Many of these seedlings have been browsed, and the repeated clipping has created bushy plants. Seedlings that have escaped browsing are now 10 to 24 inches tall.

CONCLUSIONS

A number of factors appear to have contributed to the successful germination, establishment, and survival of natural regeneration at Chimney Spring. A good seed crop was in the process of being dispersed when the initial burn was made in 1976. These seeds were deposited on a seedbed that, prior to this fire, had not been burned for the previous 100 years. Removal of this heavy forest floor created a favorable environment for seedling establishment, exposing mineral soil, releasing nutrients bound up in the forest floor material, improving moisture relations, and warming the soil surface. Ultimately, a large percentage of the original seedlings died as a result of subsequent interval burning, drought, frost heaving, and animal damage.

Remaining seedlings on rotational burning treatment plots averaged 86 per "acceptable" acre and 119 seedlings per "acceptable" acre on the plots where only the initial burn was applied. Many of the remaining seedlings showed evidence of benefiting from the release of nutrients. Their color was good, needles were well developed, and some of the larger seedlings measured more than 2 feet in height after six growing seasons.

Most of the regeneration remaining on the study area was found in existing openings, yellow pine sites, or in openings created by the fires. The area, in general, continues to be overstocked, and regeneration is neither needed, nor desirable, where stands of saplings and poles occupy the site.

This study confirms that prescribed burning can prepare a seedbed that will remain receptive for natural regeneration for several years. Although a good seed crop may not correspond with the application of a burn, enough seedlings have been observed in 1- to 4-year accumulations of litter to have a reasonable assurance that the seedbed will remain receptive to seed for some time.

Literature Cited

- Bates, Carlos G. 1923. Physiology requirements of Rocky Mountain trees. *Journal of Agricultural Research* 24:97-164.
- Biswell, H. H. 1963. Research in wildland fire ecology in California. *Proceedings of the Tall Timbers Fire Ecology Conference* 2:63-97.
- Cooper, Charles F. 1960. Changes in vegetation, structure, and growth of southwestern pine forests since white settlement. *Ecological Monographs* 30(2): 129-164.
- Cooper, Charles F. 1961. The ecology of fire. *Scientific American* 304(4):150-160.
- Dieterich, John H. 1980a. Chimney Spring forest fire history. USDA Forest Service Research Paper RM-220, 8 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Dieterich, John H. 1980b. The composite fire interval—a tool for more accurate interpretation of fire history. p. 8-14. In *Proceedings of the Fire History Workshop*. [Tucson, Ariz., Oct. 20-24, 1980]. USDA Forest Service General Technical Report RM-81, 142 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Haase, Sally M. 1981. Effects of prescribed burning on ponderosa pine seed germination in the Southwest. M.S. thesis, 67 p. Northern Arizona University, Flagstaff.
- Heidmann, L. J. 1969. Use of herbicide for planting site preparations in the Southwest. *Journal of Forestry* 67:506-509.
- Heidmann, L. J. 1976. Frost heaving of tree seedlings: A literature review of causes and probable control. USDA Forest Service General Technical Report RM-21, 10 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Heidmann, L. J., Thomas N. Johnsen, Jr., Quinten W. Cole, and George Cullum. 1982. Establishing natural regeneration of ponderosa pine in central Arizona. *Journal of Forestry* 80:77-79.
- Heidmann, L. J., F. R. Larson, and W. J. Rietveld. 1977. Evaluation of ponderosa pine reforestation techniques in central Arizona. USDA Forest Service Research Paper RM-190, 10 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Krauch, Hermann. 1936. Some factors influencing Douglas-fir reproduction in the southwest. *Journal of Forestry* 34:601-608.
- Larson, M. M. 1961. Seed size, germination dates, and survival relationships of ponderosa pine in the Southwest. USDA Forest Service Research Note RM 66, 4 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Larson, M. M., and Gilbert H. Schubert. 1969. Effects of osmotic water stress on germination and initial development of ponderosa pine seedlings. *Forest Science* 15:30-36.
- Lowdermilk, Michael M. 1930. Influence of forest litter on runoff percolation and erosion. *Journal of Forestry* 28:474-491.

- Milne, Michael M. 1978. The effects of burning, root trenching, and shading on mineral soil nutrients in Southwest ponderosa pine. M.S. thesis, 70 p. Northern Arizona University, Flagstaff.
- Pearson, G. A. 1931. Forest types in the Southwest as determined by climate and soil. U.S. Department of Agriculture Technical Bulletin 247, 144 p. Washington, D.C.
- Pearson, G. A. 1950. Management of ponderosa pine in the Southwest. U.S. Department of Agriculture Monograph 6, 218 p. Washington, D.C.
- Rowe, P. B. 1955. Effects of the forest floor on disposition of rainfall in pine stands. *Journal of Forestry* 53:342-348.
- Ryan, Michael G. 1978. The effect of prescribed burning in ponderosa pine on inorganic nitrogen content of the soil. M.S. thesis, 64 p. Northern Arizona University, Flagstaff.
- Sackett, Stephen S. 1979. Natural fuel loadings in ponderosa pine and mixed conifer forests of the Southwest. USDA Forest Service Research Paper RM-213, 10 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Sackett, Stephen S. 1980. Reducing natural ponderosa pine fuels using prescribed fire: Two case studies. USDA Forest Service Research Note RM-392, 6 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Schramm, J. R. 1958. The mechanism of frost heaving of tree seedlings. *American Philosophic Society Proceedings* 102(4):333-350.
- Schubert, Gilbert H. 1974. Silviculture of southwestern ponderosa pine: The status-of-our-knowledge. USDA Forest Service Research Paper RM-123, 71 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.
- Schubert, Gilbert H., L. J. Heidmann, and M. M. Larson. 1970. Artificial reforestation practices for the Southwest. U.S. Department of Agriculture, Agriculture Handbook 370, 25 p. Washington, D.C.
- Weaver, Harold. 1951. Fire as an ecological factor in the southwestern ponderosa pine forest. *Journal of Forestry* 49:93-98.
- Weaver, Harold. 1968. Fire and its relationship to ponderosa pine. *Proceedings of the Tall Timbers Fire Ecology Conference* 7:127-149.

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